

AN IMPACT HYPOTHESIS FOR VENUS ARGON ANOMALIES. W. M. Kaula and W. I. Newman, Department of Earth and Space Sciences, University of California, Los Angeles 90095.

Venus has two argon anomalies: a deficiency of radiogenic argon, ^{40}Ar : one-fourth as much as Earth in proportion to planet mass; and an excess of primordial argon, $^{36+38}\text{Ar}$: 80 times as much as Earth. An 860-km impactor from the outer solar system at 1.0 Ga could account for both, but is very improbable.

Relevant to the deficiency of radiogenic argon, it seems clear from the several USSR landers that the K/U ratio of Venus is about 9000, slightly less than Earth's [2]. The crust of Venus has a temperature of 740 K or more, and hence is transparent to argon diffusion. The lowness of Venus radiogenic argon has been hypothesized to imply that the bulk of radioactive heat sources in Venus are still at appreciable depth [3], thus supporting the Turcotte hypothesis of episodic evolution [4] with major outbursts of tectonic activity every few 100 My. However, it is really a constraint only on future such episodes; if they occurred in the past they should have outgassed the ^{40}Ar already generated in past episodic overturns rather efficiently, since the half-life of ^{40}K decay is only 1.3 Gy.

The ^{40}Ar is deficient with respect to a deficiency, since the ^{40}Ar in Earth's atmosphere is only one-fourth what would be expected if the crustal K/U ratio of 10,000 prevailed throughout the mantle, and outgassing were 100 percent efficient. This discrepancy is hypothesized by geochemists to indicate that the Earth's mantle is geophysically peculiar-- separations of upper and lower mantle flows over several Gy [5]- - and by geophysicists to indicate that Earth's mantle is geochemically peculiar-- fractionation differences at depth leading to an average K/U in the mantle of only 2500 [6]. Granted this second-stage problem, one would still expect hot Venus to be more effective in outgassing argon than is cool Earth, in which there may be appreciable argon trapped at depths just below 10-20 km.

Hence this relative deficiency of Venus in radiogenic argon requires explanation peculiar to Venus. The explanation may be endogenic: much lower argon diffusivity in dry Venus than in wet Earth, despite the higher temperatures, analogous to the differences in viscosity [7]. Or it may be exotic: outgassed ^{40}Ar was removed by an impact at a certain epoch in the past. If it is prescribed (1) the argon was 100 percent removed in one event; (2) the amount removed was all of the argon generated; and (3) the crustal K/U of 9000 prevailed throughout the mantle, then this event would have been at about 2.1 Ga. If the removal is less than 100 percent, then the event could be later.

On the $^{36+38}\text{Ar}$ argon excess, it has been hypothesized that it was delivered by impact of a sizable body from the outer solar system [8]. If this body has solar abundance of argon relative to its rock plus ice, and delivery was 100 percent effective, then it would not have to be very big: hardly 100 km diameter. However, it requires highly improbable dynamics [9] for a delivery to be accretive, rather than erosive. Also, such a small body would not have removed the excess radiogenic argon.

If the bolide impact occurred at 1.0 Ga, then at that time about 70 percent of the atmosphere would have had to be removed to match the presently observed ^{40}Ar , allowing for ^{40}K decay since then. To remove that much atmosphere from Venus requires about 3×10^{29} joules [10]. If the approach velocity was 30 km/sec, this amount of energy requires a body of 6.7×10^{20} kg, slightly more than $10^{-4} m_{\oplus}$. If this body has a mean density typical of the outer solar system, 2000 kg/m³, then its diameter was 860 km. Speculative questions are the amounts of primordial argon and neon retention in such a body. Table 1 is a construction assuming (1) cosmic abundances for S and more refractory elements; (2) a mean density of 2000 kg/m³; (3) a C/H atomic ratio of 1/7; (4) an atomic ratio to cosmic for argon two-thirds that of carbon; (5) an atomic ratio to cosmic for neon necessary to explain the observed abundance in Venus, assuming a neon retention at impact half that for argon. These assumptions result in a C ratio to cosmic of 0.075, and thence an Ar ratio of 0.05. The portion of this argon that must be retained at impact to match the observations of Venus atmosphere is then 0.03. Assuming a neon retention of 0.015 leads to a neon abundance in the body with a ratio to cosmic of only 0.001.

Owen et al [8] felt that the temperature required to adsorb Ne, below 20 K, was too low to occur plausibly in the nebula. However, undoubtedly there was dynamical mixing in the planetesimal phase of outer solar system formation, and our knowledge of the physics is not complete enough to exclude a retention as low as 0.1% of cosmic.

Table 1: Composition of Bolide

Element	Cosmic	Atomic	Compound	Portion of	Ratio to
	Abundance[11]*	Mass		Total mass	Cosmic
H	2.7 x 10 ⁴	1.	H ₂ O	0.171	0.00026
C	12.1	12.	CO ₂	0.119	0.075
N	2.5	14.	NH ₃	0.012	0.08
Ne	2.7	20.	Ne	1.1 x 10 ⁻⁵	0.001
Na	0.057	23.	Na ₂ O	0.011	1.
Mg	1.075	24.3	MgO	0.130	1.
Al	0.085	27.	Al ₂ O ₃	0.026	1.
Si	1.	28.1	SiO ₂	0.180	1.
S	0.515	32.	FeS	0.136	1.
Ar	0.104	36.3	Ar	0.6 x 10 ⁻⁴	0.05
K	0.0038	39.1	K ₂ O	0.001	1.
Ca	0.061	40.	CaO	0.010	1.
Fe	0.9	56.	FeO	0.195	1.
Ni	0.049	58.4	NiO	0.011	1.

*Proportionate to 1 for Si.

These properties of the 860 km body then lead to the following argon-related scenario for Venus:

Table 2 Venus Compositional history

Unit: 10¹⁵ kg

----- at 1.0 Ga -----									
Nuclide	Proto-Venus			Impactor		Impact Loss		Later Evol.	Now
²⁰ Ne	0.05	+	75.	-	74.	=			1.
³⁶⁺³⁸ Ar	0.17	+	380.	-	368.	=	12.		
⁴⁰ Ar	29.	+	0.07	-	18.	+	3.	=	14.
⁴⁰ K	60.	+	0.15	-	2.	-	24.	=	34.

The main difficulty of the impact hypothesis is the extreme improbability of a 860-km impactor as late as 1.0 Ga. The record on Earth indicates something like 10/Gy impacts of D>10 km, or m>10¹⁵ kg. Assuming $dN(m)/dm$ proportionate to m^{-q} , $q = 1.7$, yields a rate of 0.001/Gy for m>6x10²⁰ kg. Working forward from models of planetesimals in the Uranus-Neptune zone is also discouraging. Lissauer et al [12] suggest a surface density of 600/ a^2 g/cm³, where a is solar distance in AU. Integrating this from 13.5 to 38.5 AU gives 170 m_{\oplus} . Assuming an upper limit of 2 m_{\oplus} and $q=1.7$ gives 36,000 bodies greater than 10⁻⁴ m_{\oplus} . Scaling from numerical integrations in the Jupiter: Saturn zone [13] indicates that about 1/1000 of bodies would survive to 1.0 Ga. But most improbable is the perturbation of one of these bodies so that its perihelion dropped within Venus' orbit [9]. Short period comets with perihelia this low are observed, but they are drawn from a population many orders-of-magnitude larger.

Hence the impact hypothesis is, at best, a Sherlock Holmes conclusion that the improbable must be accepted, if all alternatives are impossible. But we cannot say that endogenic alternatives are impossible because argon transport within a terrestrial planet mantle, including the effects of water thereon, is still not understood-- as evidenced by the K/Ar inconsistency in Earth.

REFERENCES. [1] Donahue T.M. and Pollack J.B. (1983) *Venus*, Arizona, 1003. [2] Namiki N. and Solomon S.C. (1996) *Lun. Plan. Sci. XXVII*, 933. [3] Kaula W.M. (1995) *Science*, 270, 1460. [4] Tur-cotte D.L. (1993) *JGR*, 98, 17061. [5] Hart R. et al (1979) *Nature*, 278, 156. [6] Stacey F. D. (1980) *PEPI*, 22, 89. [7] Maxwell S.J. et al (1995) *Rock Mechanics*, Balkema, 207. [8] Owen T. et al (1992) *Nature*, 358, 43. [9] Kaula W.M. (1995) *Volatiles in the Earth and Early Solar System*, AIP, 139. [10] Ahrens T.J. (1993) *Ann.Rev.EPS*, 21, 525. [11] Anders E. and Ebihara E. (1982) *GCA*, 46, 2363. [12] Lissauer et al (1995) *Neptune and Triton*, Arizona, 37. [13] Grazier K.R. et al (1997) Statistical mechanics and the dynamics of the outer solar system. I the Jupiter: Saturn zone. *Icarus*, submitted.